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Linking economy, agro-food land use, and groundwater management to greenhouse gas emissions in Bangladesh

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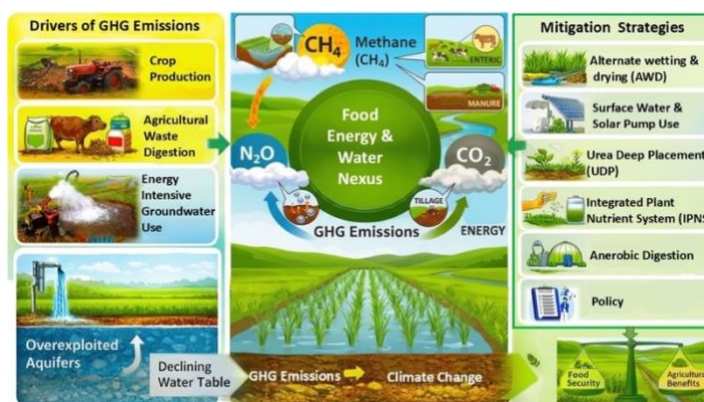
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Graphical abstract



Highlights

- Bangladesh contributes 0.48% of the world's greenhouse gas (GHG) emissions.
- Agriculture sector (38.8%) is responsible for one third of the GHG emissions.
- Rice cultivation is a major source of agricultural sector GHG emissions.
- Groundwater, nutrients, and waste management practices are key drivers of GHG emissions.
- Climate change exacerbates groundwater stress and GHG emission risks.

Abstract

The agricultural sector in Bangladesh is a significant contributor to greenhouse gas (GHG) emissions, driven by intensive crop production, irrigation-dependent groundwater extraction, and associated energy use. At the same time, high-input agriculture remains essential for food security and economic growth, creating a critical sustainability challenge. This study provides an integrated overview linking Bangladesh's economic context, agri-food land use, and groundwater management to GHG emissions. Based on a synthesis of peer-reviewed literature, national statistics, and international datasets, the review examined how dry-season irrigation—largely dependent on diesel and electricity-powered groundwater pumping—drives energy demand and emissions. The analysis highlights the influence of climatic variability and geographic conditions on emission patterns, with methane (CH₄), nitrous oxide (N₂O), and carbon dioxide (CO₂) identified as the dominant gases from agricultural activities. The review further evaluates mitigation options, including alternate wetting and drying (AWD), surface water use, solar irrigation, prilled urea utilization (PU), urea deep placement (UDP), integrated plant nutrient system (IPNS), and anaerobic digestion. Existing policy frameworks and groundwater management practices are also assessed. The findings

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underscore the need to better integrate groundwater management with low-carbon agricultural practices to reduce emissions while sustaining productivity under climate change in Bangladesh.

I Introduction

Bangladesh is a densely populated nation in South Asia and ranks as the 2nd largest economy. It also ranked 35th in the world (Adib et al., 2024). Despite its economic growth, it contends with the intricate balance between rapid economic growth and ensuring food security for its increasing populace and reducing the growing impacts of climate change. Bangladesh's economy is showing diversifying characteristics, where agriculture remains a dominant sector. Although direct contribution from agriculture to the Gross Domestic Product (GDP) has shown a declining trend, standing at less than 12% in 2021, it continues to be the "lifeblood" of the economy, employing a significant part of the labor force, which covers 40% of the total employment in 2022 (Chowhan et al., 2023; Manik, 2023). The need for agro-food production to feed a large and expanding population places substantial pressure on natural resources. Bangladesh is limited by land availability, where land use dynamics are shaped and influenced by agricultural intensification, urbanization, and environmental challenges (Parvin et al., 2024). The country has historically observed significant agricultural land use changes, which are driven by the widespread adoption of high-yielding rice varieties and modern green technologies, leading to increased land use intensity (Ullah and Uddin, 2021; Parvin et al., 2024). However, this expansion comes at a cost of losing 1% arable land annually (Pervez et al., 2021). This transformation highlights the need for balance between productive capacity and the long-term sustainability of land resources (Parvin et al., 2024).

Bangladesh's agricultural success in achieving self-sufficiency in rice production is due to its heavy reliance on irrigation, with groundwater serving as the dominant source (Rahman and Parvin, 2009). Approximately 77% of the total irrigated area depends on groundwater, primarily extracted through shallow tube wells (Rahman and Parvin, 2009). While other studies also suggest that 90% of irrigation activities rely on groundwater (Monir et al., 2022). This large amount of groundwater abstraction for agricultural activities, particularly for dry-season Boro rice cultivation, raises significant concerns about groundwater depletion (Amarasinghe et al., 2014; Mollah, 2020). The energy-intensive process of pumping groundwater for irrigation is largely dependent on diesel fuel, and it is also subsidized by the government. It is a major contributor to the agricultural

sector's greenhouse gas (GHG) emissions (Maniruzzaman et al., 2025).

The nexus between groundwater management and GHG emissions points towards a significant environmental and developmental challenge for the sustainability of Bangladesh's economy. The agriculture sector itself is a leading emitter of GHG in Bangladesh. Increasing modernization, together with the cultivation of irrigation-intensive crops such as rice, constitutes a significant contributing factor (Aziz and Chowdhury, 2022). While total irrigation water-driven GHG emissions in Bangladesh amount to approximately 2.27 million tons of CO₂ equivalent (CO₂e) during the dry season, groundwater pumps alone contribute 2.04 Mt CO₂e (Maniruzzaman et al., 2025). Raihan et al. (2023) show that increases in agricultural land, crop production, and energy use directly correlate with increased GHG emissions. Even a modest change in emissions from irrigation pumps can cause significant impacts on the total agricultural emissions (Ali et al., 2017).

Groundwater uses also cause changes in soil moisture regimes, redox conditions, and nutrient dynamics, which are key reasons behind methane (CH₄) and nitrous oxide (N₂O) emissions from agricultural lands, particularly during flooded conditions. Generally, continuous flooding in irrigated agricultural fields promotes anaerobic soil conditions that enhance the production of CH₄, while excessive or poorly managed fertilizer application elevates N₂O emissions. These gases are responsible for climate change and largely contribute globally. The Asian Development Bank (ADB) reported that Bangladesh may experience a 2% GDP loss annually by 2050 due to climate change impacts (ADB, 2014). This complex interplay between climate change and the economy raises the necessity of a comprehensive understanding to develop sustainable and climate-resilient agricultural practices.

Previous research on agricultural GHG emissions and groundwater management is largely fragmented and sector-specific. Most agricultural GHG emission studies focus on individual sources, such as CH₄ from rice cultivation or N₂O from fertilizer use. They are not adequately accounting for groundwater abstraction and energy-intensive irrigation as interconnected emission drivers. Conversely, groundwater research often provides more emphasis on hydrological sustainability while neglecting climate implications. The lack of integration of scientific evidence with policy and

governance frameworks restricts understanding of synergies and trade-offs. To overcome this, this study aims to provide a comprehensive overview of agricultural and groundwater management and land use practices in Bangladesh, along with detailed insights into GHG emissions from these activities. It also focuses on government initiatives and collaborative partners' efforts to mitigate GHG emissions. The main objectives of this study are to find out the GHG emissions from the agricultural sector and its management procedures in Bangladesh; evaluate the sustainability of groundwater use in the agricultural sector and find out the intricate relationship between groundwater management practices and GHG emissions.

2 Methodology

2.1 Systematic review

This study evaluates the intricate relationships among GHG emissions, agricultural practices, and groundwater management using a systematic and comprehensive review process (**Fig. 1**). Systematic literature reviews are well known for their robust methods of synthesizing existing knowledge, especially in interdisciplinary fields (Mengist et al., 2020; Varsha et al., 2024), and are important for providing transparent and reproducible overviews of research on specific topics (Okoli, 2015).

A multi-faceted and systematic literature survey was conducted across multiple academic and literature databases to capture scientific, management, and policy related information. Peer-reviewed publications were collected from Google Scholar, Web of Science, and Scopus. Relevant policy, legal, and project documents were collected from official repositories, including UNFCCC, IPCC, FAO, UNEP, World Bank, and national government portals related to agriculture, water resources, and climate change. The GHG emissions, economic data, and sector-wise emissions were collected from Our World in Data (Data, 2024).

2.2 Keyword development

A comprehensive set of keywords, as well as their synonyms, was utilized to capture the breadth of the research objectives. The development of keywords and selection of databases is a fundamental step in systematic literature and policy reviews (Mengist et al., 2020). These keywords were structured into distinct categories for targeted findings:

Agricultural GHG emissions: "agricultural greenhouse gas emissions," "crop production greenhouse gas emissions," "livestock greenhouse gas emissions," "N₂O emission from fertilizer use," "agricultural energy use," and "greenhouse gas emission from energy consumption in agricultural sector."

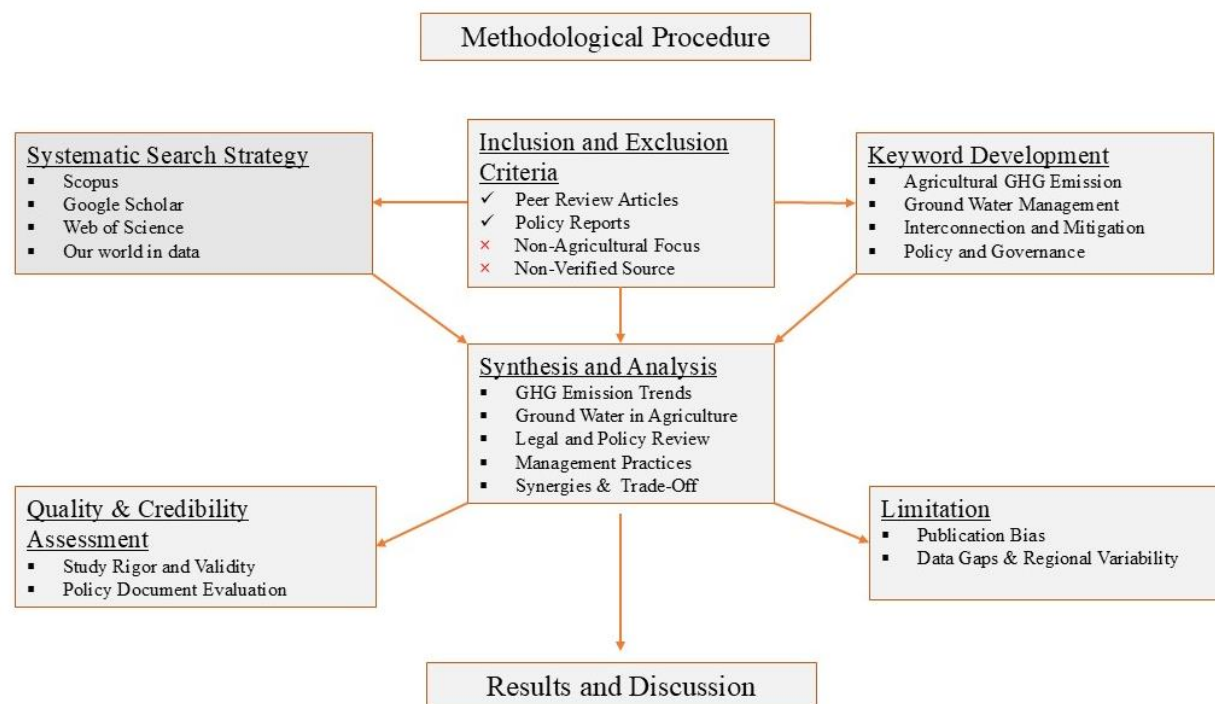


Figure 1. Methodological procedure of the study.

Groundwater use and management: "groundwater use and abstraction in agriculture," "irrigation groundwater management," "sustainable ground and surface water use," and "groundwater management policy."

Interconnections and mitigation: "agricultural process and water energy nexus," "relation between water use in agriculture and greenhouse gas emission," "irrigation emissions reduction," and "sustainable agriculture water management."

Policy and governance: "agricultural policy environmental impact," "groundwater management law and policy," "energy consumption law and policy," "greenhouse gas emission law and policy," "UN reports agriculture climate," and "project sustainable water."

2.3 Inclusion and exclusion criteria

A set of criteria was applied to select relevant documents for this study. This criterion was categorized into two groups: inclusion and exclusion criteria. Inclusion criteria include (i) peer-reviewed articles, governmental reports, UN documents, and publications from reputed non-UN organization; (ii) time period between January 1, 2000, and December 31, 2025; (iii) studies addressing GHG emissions from the agricultural sector, groundwater uses in agriculture, or the direct/indirect relationship between the two; (iv) documents that detail policies, laws, and projects related to sustainable agriculture, groundwater management, energy consumption, and climate change mitigation/adaptation; and (v) publications available in English. The exclusion criteria are (i) grey literature, which lacks institutional authorship, transparent methodologies, or evidence of peer review (e.g., personal blogs and unverified news articles); (ii) studies that focused solely on surface water management without implications for groundwater; (iii) studies that focused solely on non-agricultural GHG emissions or water management unrelated to agriculture; and (iv) duplicate documents across different databases.

2.4 Synthesis and analysis

A thematic narrative synthesis was used to integrate outcomes across diverse source types. Thematic synthesis is a well-known method in systematic reviews to bring together and integrate findings from multiple qualitative studies, developing descriptive themes and generating analytical themes (Thomas and Harden, 2008; Macura et al., 2019). The analysis was structured around key themes: (i) factors and patterns of GHG emissions in Bangladesh, (ii) GHG emissions from agricultural sectors, (iii) groundwater reliance and stress in agricultural landscapes, (iv) existing

legal and policy frameworks governing agriculture and groundwater use, (v) management practices influencing both GHG emissions and water sustainability, (vi) intricate relations between groundwater management and GHG emissions, and (vii) conceptual interconnections have been established to show how groundwater use influences emissions, especially energy use for irrigation and soil-based emission processes.

2.5 Quality control and assurance

Methodological rigor, objective clarity, and data and analysis consistency were used to evaluate peer-reviewed papers. Legal authority, implementation status, and conformity with international frameworks were taken into consideration when evaluating policy papers and institutional reports. To ensure credibility, sources from prominent publications and globally renowned organizations were given priority.

3 Results and discussion

3.1 Overview of agri-food system in Bangladesh

Bangladesh is located in the eastern part of South Asia. It shares borders with Myanmar on the southeast, the Bay of Bengal on the south, and India on the west, north, and east. The total area is 147,570 km², which is the world's 94th largest country. It is the world's 6th most densely populated country, having 166.50 million people, and ranked 8th in the world (BBS, 2020). According to the World Bank, its annual GDP growth rate in 2024 was 4.23% (Raihan et al., 2024). However, the GDP was higher in the previous year. This may be due to inflation and political instability. Aside from these constraints, Bangladesh is still growing its economy. One of the major contributors to this GDP growth is the agriculture, forestry, and fishing sector. The agricultural sector not only promotes Bangladesh's economic growth but also ensures food security. In 2024, the contribution of this sector was 11.16% (Manik, 2023). Almost 40% of the labor force is involved in the agricultural sector (Chowhan et al., 2023). The agri-food system is a highly diversified system that encompasses crop production, livestock, fisheries, food processing, and retail distribution. Rice dominates the crop sector in Bangladesh, occupying most of the cultivated land, while fisheries and aquaculture make it one of the world's top producers. Livestock and poultry provide critical income for rural households, particularly

women. The rapid expansion of urban food markets and food processing industries is creating new value chain linkages between farmers, traders, processors, and consumers. However, these value chains remain fragmented; inadequate storage, limited cold-chain infrastructure, and inefficient transportation systems contribute to high post-harvest losses and constrain market efficiency.

3.2 Greenhouse gas inventories: key sources and distribution pathways

The GHG constitutes several gases, for example, carbon dioxide (CO₂), fluorinated gases (HFCs, PFCs, and SF₆), water vapor (H₂O), CH₄, and N₂O that are responsible for the increase in global temperature (Chen et al., 2024). The unit of GHG emission is CO₂e, which means the effect of different GHGs in terms of the quantity of CO₂ that would cause the same effect as all the GHGs. The amount of GHG emissions showed a fluctuating pattern. A gradual upward trend was observed between 2015 and 2019, followed by a pronounced decline in 2020. Thereafter, the trend rebounded, reaching levels comparable to the pre-2020 period by 2022 (Fig. 2).

At the global level, GHG emissions are commonly attributed to eleven principal emitting sectors. They are agriculture sources, land use and forestry sources, waste management sources, buildings and infrastructure sources, industrial sources, manufacturing and construction sources, transportation sources, electricity and heat generation sources, energy production sources, fuel combustion and bunker fuel sources (Fig. 3). Globally, the agricultural sector is responsible for the highest proportion of GHG emissions

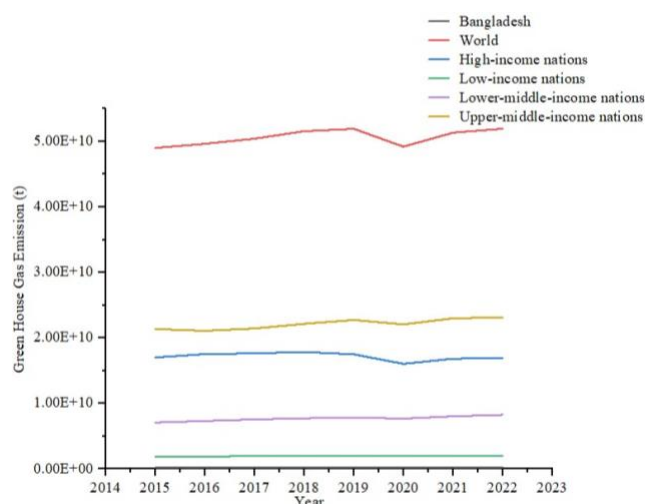


Figure 2. Global pattern on greenhouse gas (GHG) emission from 2015 to 2022.

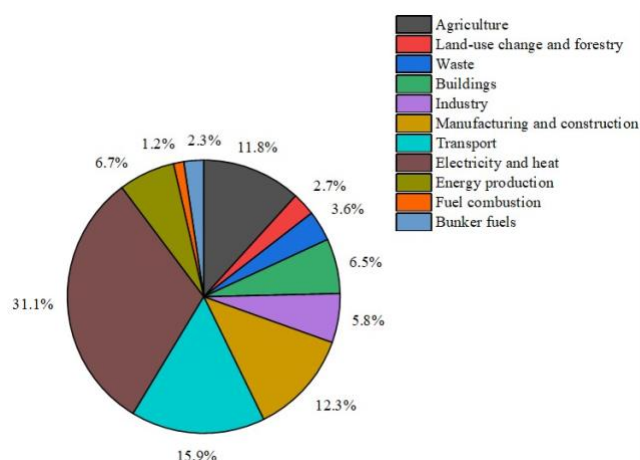


Figure 3. Sector wise contribution to the global greenhouse gas (GHG) emission.

(31.1%), in contrast to fuel combustion, which contributes only 1.2% (Greenhouse Gas Emissions by Sector, 2025).

Bangladesh only contributes 0.48% of the world's GHG emissions. High-income (33.92%) and upper-middle-income (43.69%) nations account for the majority of global emissions, with lower-middle- and low-income nations contributing less than 20%. Despite a lower contribution to GHG, Bangladesh is highly affected by the impact of GHG emissions. Bangladesh followed a steady trend for the emission of GHG from 2015 to 2022. Agriculture remains the dominant source (38.8%), with electricity and heat generation contributing 19.6%. These sectors combined account for approximately 59% of total emissions, while the waste sector contributes a further 9.2% (Fig. 4a). In low-income countries, GHG emissions are largely driven by land use change and agricultural activities. However, as income levels rise, this pattern shifts, with electricity generation and transport becoming the dominant sources of emissions (Fig. 4). Although Bangladesh contributes minimally to global GHG emissions, it has undertaken efforts to pursue low-emission development pathways. National emissions are dominated by non-CO₂ gases (75.4%), particularly CH₄, N₂O and fluorinated gases (HFC, SF₆, and PFC), whereas CO₂ contributes only 24.6% (Greenhouse Gas Emissions by Gas, 2025). This contrasts sharply with the global profile, where CO₂ accounts for approximately 71.6% of total emissions. This is due to the large population in Bangladesh being involved in agricultural activity. The reason behind the non-CO₂ gas responsibility in GHG emissions in Bangladesh is due to their chemical characteristics. CH₄, often known as a flow pollutant (Fernández-Amador et al., 2020), is mostly emitted from the livestock digestion and manure management processes (Tubiello et al., 2015). On the

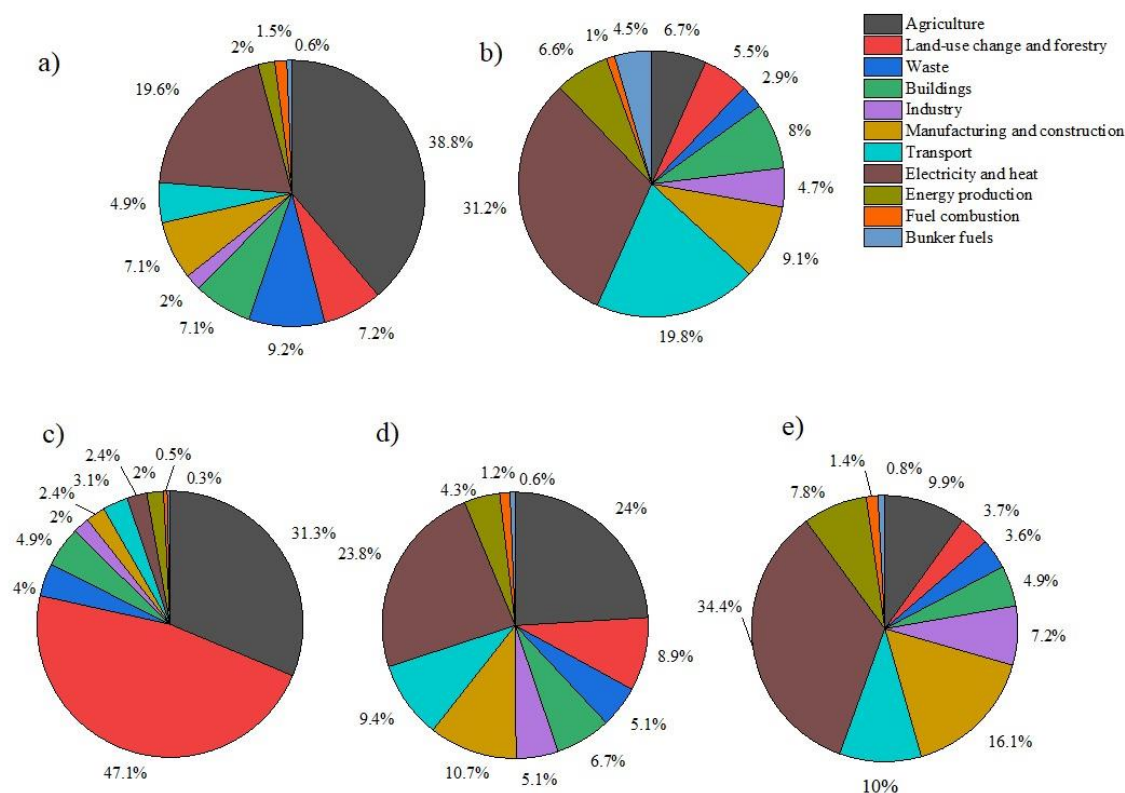


Figure 4. Sector wise contribution to greenhouse gas (GHG) emissions across different economic group and Bangladesh. a) Bangladesh, b) high income nations, c) low-income nations, d) lower middle-income nations, e) upper middle-income nations.

contrary, CO₂ is a stock type of pollutant that is emitted due to various activities, such as energy production procedures, peatland drainage systems, and burning crop residue (IPCC, 2022). Moreover, crop leftovers and nitrogen fertilizers employed in agricultural processes are the sources of N₂O (Haider et al., 2020). CH₄ and N₂O are responsible for a significant part of agricultural emissions, which are commonly expressed as CO₂-equivalents due to their Global Warming Potential (GWP) across a 100-year time period (Lynch et al., 2021).

3.3 Management of greenhouse gas emissions

Food accounts for over one-third of GHG emissions worldwide. In Bangladesh, rice accounted for almost 60% of all emissions from agriculture, while rice and livestock together contributed above 90% of the emissions. Among the top 10 rice-producing countries, Bangladesh is ranked 6th for total GHG emissions and 7th for CH₄ emissions (Biswas et al., 2022). In the case of crop cultivation, Bangladesh targeted lower emissions at short-term (2030) and long-term (2050) mitigation than Business As Usual (BAU). Mostly CH₄ and N₂O are produced as GHG from the rice cultivation process. The GWP of CH₄ is 273 times higher

than CO₂, while N₂O is 27–30 times higher over a 100-year period (Chauhan et al., 2017).

The CH₄ emissions from rice cultivation primarily arise from anaerobic soil conditions induced by continuous flooding. In Bangladesh, rice farmers commonly maintain prolonged inundation of crop fields to support higher production, which creates persistently anaerobic environments that favor methanogenic microbial activity and consequently enhance CH₄ emissions from rice fields. However, the use of water varies by location, farmer, and climate pattern. On average, approximately 1,606 L of water is used to produce 1 kg of rice in Bangladesh. However, only about 661 L of this water is directly consumed through crop evapotranspiration, accounting for roughly 41% of the water supplied, while the remaining water is lost through seepage, percolation, runoff, and non-productive evaporation. In the case of rice cultivation, an average of 9,900 kg of CO₂ is emitted per hectare of land (Biswas et al., 2022). This emission can be reduced by utilizing some alternative practices, such as alternate wetting and drying (AWD), the system of rice intensification (SRI), and integrated crop management. AWD can reduce the water use in the crop-yielding process by up to 38% without any yield penalty compared to continuous flooding and the average cumulative

CH₄ emissions by up to 37% (Islam et al., 2020). In addition, organic amendments such as manure or crop residues can increase CH₄ emissions if applied immediately before flooding due to increased labile carbon availability. However, composting residues or applying them during dry periods can substantially mitigate this emission. On the other hand, N₂O is mainly produced from nitrogen (N) fertilizer application and the use of organic amendments in agricultural fields. Typically, the average rate of N fertilizer use is 120–130 kg N ha⁻¹ (Alam et al., 2023). Nevertheless, 1–5% of the nitrogen fertilizer goes away into the atmosphere as N₂O during the fertilization process (Chauhan et al., 2017). N₂O emissions from agricultural soils are responsible for approximately half of all human-caused sources in the atmosphere (Zhang et al., 2024). Using urea deep placement (UDP) and an integrated plant nutrient system (IPNS) (which integrates urea and poultry waste) are two scientifically proven management options for reducing N₂O emissions from agricultural fields. UDP enhanced rice harvest by 21% and N recovery rate by 58% contrasted to prilled urea (PU) (Islam et al., 2022). That will decrease the use of N fertilizer in agricultural fields and reduce the N₂O emission.

Livestock manure contributes significantly to agricultural CH₄ and N₂O emissions, particularly during anaerobic storage and land application. Cattle farming (cows, buffalo, sheep, and goats) and poultry produce more than 155.8 million tons of manure annually (Khanam et al., 2019), which emits about 176.75 million kg of CH₄, with cattle accounting for 87% of this output (Samad, 2020). Anaerobic digestion is a widely recognized and accepted method as the most effective mitigation option, as it captures CH₄ for energy production while substantially reducing net CH₄ emissions from manure management systems. Other types of management, such as the use of livestock manure, may reduce the import of about 40–45% of chemical fertilizers, such as urea (N), TSP (P), and MoP (K), and this may help to generate rural employment (ILMM, 2015).

3.4 Climate strategies: policies, mitigation, and adaptation efforts

3.4.1 Existing government strategies

Bangladesh aims to minimize 21.85% GHG emissions by 2030 with domestic and international support. The energy sector aims to reduce emissions by 5% using domestic resources and up to 15% with donor support by 2030, as opposed to the BAU scenario. On the other hand, the agriculture sector, forestry sector and other land use (AFOLU) have committed to reducing emissions by 5.26% by 2030 in their revised Nationally Determined

Contributions (NDC). Additionally, it seeks to cut emissions of CH₄ by 17% along with black carbon by 40% until 2030 in comparison to the BAU scenario (NDC, 2021).

Bangladesh has developed a comprehensive framework and guideline for addressing climate change impact nationwide through long-term strategic plans like the Bangladesh Delta Plan 2100, which integrates adaptation pathways of clean and safe water, food safety, economic expansion, and sustainability of the environment and resilience to extreme climatic events via adaptive delta management (Hadi, 2019; Kulsum et al., 2021). The Eighth Five-Year Plan is pointing out renewable energy integration, targeting additions like 2,362 MW from renewables by 2025, alongside guidelines in the 2nd Perspective Plan (2021–2041) and BDP2100 for ensuring energy security (Jamal et al., 2021; Groh et al., 2022).

Bangladesh's revised NDCs commitment to 5,026 MW of renewable energy capacity by 2030 (unconditional/conditional), which will align with the Paris Agreement for GHG reductions (5% unconditional, and up to 15% with support) and be supported by the Renewable Energy Policy aiming for 10% renewables by 2020/2021 via solar, wind, and incentives (Gulagi et al., 2020; Rahman et al., 2022; Akter and Nasher, 2025). The Master Plan for energy efficiency and conservation up to 2030 promotes efficient resource use (Rahman et al., 2021), while power purchase agreements facilitate rooftop solar and grid integration for private sector renewables (Sadowski et al., 2021). The adaptation strategies are embedded in the Mujib Climate Prosperity Plan-2030, emphasizing proactive risk management, disaster financing, poverty reduction, and social inclusion. The Bangladesh climate change trust fund provides domestic financing support (USD 100 million annually) for resilience under Bangladesh Climate Change Strategy and Action Plan (BCCSAP) pillars (Stock et al., 2021). These strategies align with the Paris Agreement and Sustainable Development Goals (SDGs), which incorporate renewables (e.g., solar energy, wind energy, and hydropower) into Five-Year Plans like the Seventh/Eighth for low-carbon growth (Stock et al., 2021; Groh et al., 2022), with SREDA (2012 Act) responsible for renewable energy promotion, with BDP2100 as a "living document" mainstreaming climate into development.

3.4.2 Improvement options

In case of strengthening policy implementation and governance, the government should prioritize systemic improvements in emission inventories, equitable fund allocation, subsidy provision, and robust data collection for agricultural adaptation, ensuring better reach to vulnerable

groups to address gaps in monitoring, coordination, and data accuracy across policies like the Bangladesh Delta Plan 2100 and NDCs (Hossain et al., 2025; Kashem, 2025). Enhancing transparency, data availability, and reporting mechanisms in climate finance projects, while simplifying complex funding modalities, would improve oversight and accessibility. While in the case of advancing climate finance mechanisms, the climate change trust fund allocates consistent funding levels to promote quality project proposals through capacity building, minimize political influence in decisions, and strengthen control over implementing ministries to overcome current constraints (Rahman and Huang, 2019). Introducing decentralized climate finance and local government capacity-building can be a way to scale community-led resilience, complemented by World Bank-style co-benefits in fiscal reforms and infrastructure (Kashem, 2025). In case of boosting renewable energy, revised and updated renewable energy policy 2008 and draft national solar energy roadmap by incorporating USAID 2023 recommendations, such as strategic methodologies for solar and biomass scaling, alongside de-risking mechanisms like time-bound land acquisition and improved finance allocation to attract investments can be an effective way to boost up the production of renewable energy and reducing GHG emission (Akash et al., 2024). Leveraging the regional cooperation for technology scalability and policy alignment toward net-zero emissions can be another way to improve climate strategies. The case of enhancing adaptation and inclusivity incorporates long-term research, monitoring, and evaluation on future climate impacts into policies such as the Mujib climate prosperity plan and eighth five-year plan, addressing uncertainties in community livelihood adaptations (e.g., farmer choices in agriculture) for more robust delta management (Kulsum et al., 2021). Plan-do-check-act policy should be prioritized in every management procedure and strategy. Prioritizing equity and inclusiveness by ensuring vulnerable communities, women, and marginalized groups participate in decision-making and resource allocation.

3.5 Groundwater use dynamics and greenhouse gas emission

3.5.1 Groundwater irrigation

In Bangladesh, the aquifer is primarily deposited by the Ganges-Brahmaputra-Meghna (GBM) river system (Sultana et al., 2014). The geological setting makes the aquifer one of the most productive aquifer systems globally (Majumder and Shimada, 2019). An estimated 32 km³ of groundwater are extracted annually in Bangladesh, which is equivalent to around 4% of all groundwater withdrawals worldwide

(Shamsudduha et al., 2019; Mirea and Nistoreanu, 2021). Approximately 90% of the abstracted groundwater is used for irrigation, while the remaining 10% is allocated for domestic and industrial purposes (Shamsudduha et al., 2019). The estimation of groundwater use for irrigation typically relies on information such as the quantity of both shallow and deep irrigation wells and the irrigated area, while household water use is calculated based on the population size in each geographic area (Shamsudduha et al., 2019).

Groundwater irrigation is a critical component of Bangladesh's agricultural sector, underpinning food security and the extensive cultivation of high-yielding rice varieties. Nearly half of the country's total cultivated land relies on irrigation, with the highest levels of irrigation concentrated in the north-central and western regions, including Dhaka, Mymensingh, Rajshahi, Rangpur, and Khulna (BBS, 2020). This extensive irrigation supports intensive cropping systems, while Boro rice alone occupies nearly three-fifths of the irrigated agricultural area (BBS, 2020). Approximately 90% of the total groundwater extracted is dedicated to agriculture (Shamsudduha et al., 2019). By 2013, the quantity of shallow pumping/tube wells (less than 100 m deep) increased significantly from 0.1 million in 1981 to over 1.5 million (Ahmed et al., 2025). In 2010, the estimated groundwater abstraction in Bangladesh exceeded 33 km³, with 95% of this volume utilized for dry season farming (Mainuddin et al., 2015), capable of supplying 5 million hectares with a water depth of 650 mm (Mirea and Nistoreanu, 2021). The area irrigated by groundwater (both shallow and deep tube wells) is approximately 4.2 million hectares, while surface water irrigates 1.03 million hectares using low-lift pumps (Boral Doal et al., 2023).

3.5.2 Surface water versus groundwater irrigation

The strategic choice between surface water and groundwater for irrigation is primarily influenced by several factors such as availability, reliability, and cost-effectiveness. Groundwater has historically been favored due to its availability and reliability, especially during the dry season when surface water availability is scarce or unpredictable. This preference is also influenced by groundwater's quality and local availability, requiring minimal treatment. On the other hand, Bangladesh has a large number of surface water resources due to high monsoonal rainfall and an extensive river network spanning approximately 22,000 km. It is dominated by the GBM river basins, which collectively cover nearly 80% of the national territory (FAO, 2011). Total surface water flow is estimated to be 795,000 Mm³ (Rodriguez, 2018), considerably higher than the approximately 21,088 Mm³ of groundwater resources

(Mridha and Rahman, 2021). In addition, nearly 85% of annual precipitation occurs during the monsoon season (June–October), leading to frequent inundation of low-lying areas and heightened flood vulnerability. Despite this abundance of surface water, it only contributes around 20% of total irrigation coverage (BBS, 2020). Groundwater and surface water use in irrigation exhibited contrasting trends over time. The total share of surface water irrigation declined markedly from 60–65% in the early 1980s to approximately 20–25% by the late 2010s, while groundwater irrigation expanded from about 40% to nearly 80% (BADC, 2022). This may be due to cost-effective technology being available over time. However, regional variation exists. Surface water irrigation remains more common in the northeastern and south-central regions. Its intensity is substantially lower than groundwater-based irrigation, particularly in the northwestern region of Bangladesh (BBS, 2020).

3.5.3 Groundwater quantity and quality

Groundwater is the primary water source of dry-season irrigation and drinking water in Bangladesh, which plays a critical role in food security and livelihoods. Its availability largely depends on monsoonal recharge from rainfall, rivers, and surface water bodies (GED, 2018). Recharge and abstraction showed strong spatial variability, with higher recharge rates in the northwestern and western regions. This region is also a major river corridor, where intensive irrigation pumping has also induced additional recharge (Shamsudduha et al., 2011). However, sustained dry-season extraction has been responsible for declining groundwater levels and pronounced seasonal fluctuations, particularly in the northwestern and north-central regions, reducing the effectiveness of shallow tubewell (Mojid et al., 2021). Where land surfaces are relatively impermeable, intensive groundwater withdrawals lead to a net depletion in groundwater storage, estimated at approximately 1 km per year in Bangladesh (Nowreen et al., 2020). In contrast, groundwater levels in coastal areas remain shallow but are highly constrained by saline water intrusion (Islam et al., 2017; Le et al., 2025). Groundwater quality degradation by human and natural processes further limits usability. Arsenic contamination affects 61 districts and exposes an estimated 35–77 million people to chronic health risks (Saha et al., 2019). Elevated iron, manganese, and increasing salinity, exacerbated by sea-level rise and land use change, also pose additional challenges for sustainable groundwater use.

3.5.4 Groundwater management

Bangladesh is rich in extensive surface and groundwater bodies, including numerous rivers, wetlands, floodplains,

reservoirs, and aquifers (Adel, 2012). Despite this, groundwater remains the dominant source of irrigation and domestic water supply, accounting for over 70% of irrigation use (BADC, 2022) and nearly 80% of daily water extraction nationwide. To address growing pressure on groundwater resources and incorporate sustainable groundwater use, the Government of Bangladesh (GoB) has introduced several regulatory measures over time. The Groundwater Management Ordinance of 1985 required a license for irrigation withdrawals but was revoked in 1992. The Water Act of 2013 was introduced, and it empowered a high-level executive committee and the National Water Resources Council to regulate groundwater abstraction in water-stressed areas by setting safe yield thresholds. More recently, the Underground Water Management Law of 2018 reinstated licensing requirements, assigning local governments the responsibility for enforcement through Upazilla-level irrigation committees. The law prescribes minimum service areas and spacing between irrigation pumps (for 0.5 cusecs discharges 250 m, and 2 cusecs discharges 800 m) and restricts pump installation near perennial rivers (2 km away from the perennial river source), aiming to reduce over-extraction and promote sustainable groundwater use. However, the groundwater management system and policy face significant challenges. The minor irrigation policy 2017 and the groundwater management law 2018 have been stated to be reducing groundwater abstraction from the aquifer and promoting surface water use; they often lack specific quantitative targets or action plans. Lack of coordination among different government officials involved in water management is another constraint. This leads to inconsistent enforcement and inefficiencies in groundwater management. Now, groundwater is managed by seven different organizations, highlighting the need for better integration and coordination between their efforts in implementing water management policy and law (Boral Doal et al., 2023). Moreover, existing institutions frequently struggle with inconsistent enforcement, political interference, corruption, absence of public participation, and poor coordination among various bodies (Bhattacharjee et al., 2019).

To improve the efficiency of groundwater management policies and implementations, a multifaceted strategy is essential. Firstly, management should incorporate an integrated water resources approach that recognizes the interconnectedness of surface and groundwater to address both quantity and quality aspects (Mukherjee et al., 2024). Secondly, it is necessary to enhance monitoring and data collection by implementing advanced systems to track groundwater levels and quality. This data should be

accessible for informed decision-making. Precise hydrogeological parameters and comprehensive monitoring networks are important for predicting and managing groundwater changes effectively (Mustafa et al., 2019; Hassan et al., 2021). Thirdly, policies should actively promote and incentivize water-saving technologies and practices, such as alternate AWD for rice cultivation and using surface water, which can significantly reduce groundwater abstraction (Boral Doal et al., 2023). Fourthly, exploring and implementing artificial recharge methods and managed aquifer recharge techniques, particularly in drought-prone areas, offers a viable pathway to replenish depleted aquifers and enhance water security (Rahman et al., 2018). Furthermore, empowering local communities and institutions in groundwater management through decentralization funds and improved local governance can lead to equitable outcomes (Bhattacharjee et al., 2019). Strengthening the existing legal framework with clear, enforceable abstraction limits, robust enforcement mechanisms, and appropriate penalties for non-compliance is also important (Bhattacharjee et al., 2019). Finally, it is essential that policies integrate strategies for adapting to climate change to effectively address the impacts of changing rainfall patterns and rising temperatures on the nation's groundwater resources (Sarkar et al., 2024).

3.5.5 Energy consumption and its emission implications

The intensive use of groundwater for irrigation in Bangladesh is crucial for agricultural productivity and food security. However, it has significant implications on economy and the environment, particularly on GHG emissions. Irrigation water delivery in Bangladesh largely depends on diesel pumping. Approximately 1.34 million diesel-operated pumps and 240,000 electric pumps are currently working in irrigation sectors (Saleh et al., 2022). Diesel engines account for nearly 85% of irrigation pumps, while the remaining 15% rely on electricity. Most of which are subsidized. Operating this pump-based irrigation system requires an estimated USD 1 billion annually (Saleh et al., 2022), and electricity demand for irrigation alone reaches about 2,000 MW during peak periods (Foster et al., 2020).

The intensive use of energy in the irrigation process contributes substantially to national GHG emissions. Combustion of diesel fuel and electricity generation are largely dependent on the use of fossil fuels. That makes irrigation a significant emissions source within the agricultural sector. Dry-season irrigation sector-related emissions are estimated at approximately 2.27 million tons of CO₂e, representing around 4% of total agricultural GHG emissions in Bangladesh (Maniruzzaman et al., 2025).

Groundwater abstraction is the dominant contributor, accounting for about 2.04 Mt CO₂e per season, compared to only 0.23 Mt from surface water irrigation (Maniruzzaman et al., 2025). Diesel-operated pumps alone are estimated to emit approximately 3.22 Mt of CO₂ annually, indicating their disproportionate role in the carbon footprint (Foster et al., 2020).

In response, the renewable energy-based irrigation processes, particularly solar photovoltaic (PV) pumps, are gaining attention as a useful and feasible mitigation strategy. Replacing a 1 kW diesel pump with a solar PV system can reduce emissions by approximately 0.9 t CO₂ annually (Sarkar and Ghosh, 2017). Solar irrigation pumps also offer economic advantages, with payback periods ranging from 2 to 9.33 years (Hossain et al., 2015; Sarkar and Ghosh, 2017), while enhancing energy security and aligning with national climate commitments (Khadka et al., 2023). Despite these benefits, solar pumps currently serve less than 1% of the irrigated area, leaving irrigation as the second-largest diesel-consuming sector in Bangladesh after transportation (BADCO, 2022). This sector should be subsidized to grow interest in solar pump use during irrigation. Moreover, the development of surface water networks in irrigation areas would not only reduce groundwater abstraction but also enhance groundwater recharge across the country.

4 Conclusion

Bangladesh will continue its robust economic growth and the foundational role of its agricultural sector in ensuring food security. This critical sector imposes contrasting pressures on the nation's environment and economy. This study highlights that current groundwater management practices, GHG emission strategies and climate change policies, if continued without reform, may exacerbate both climate and resource sustainability challenges. Reducing emissions from the agriculture sector requires a combination of technological, managerial, and policy interventions. Water-efficient irrigation methods such as AWD can substantially lower CH₄ emissions from rice cultivation, while improved prilled urea utilization, using urea deep placement and an integrated plant nutrient system can reduce the NO₂. In addition, anaerobic digestion of agricultural residues and manure offers a viable pathway to mitigate emissions while generating renewable energy. Integrating these measures and groundwater governance frameworks can simultaneously enhance agricultural productivity and lower GHG emissions by strengthening the resilience of Bangladesh's agri-food system under climate change.

5 Data availability statement

The data may be made available upon request from the corresponding author.

6 Ethical statements

Not applicable.

7 Conflict of interest

The authors declare that there is no conflict of interest.

8 Author contributions

M.A. Habib: Conceptualization, data curation, formal analysis, and writing – original draft. P. Bhattacharya: Writing – review & editing. M.R. Haque: Writing – review & editing. T.K. Saha: Writing – review & editing. All the authors approved the final version of the manuscript.

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